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MODELLING OF PICOSATELLITE CONSTELLATION-BASED NETWORK AND EFFECTS ON QUALITY OF SERVICE

by

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The military applications for miniature, low-cost satellites that could be quickly launched to provide ad-hoc tactical networks have risen in recent years. Currently, the smallest practical variant of these miniaturized satellites is known as the picosatellite. In order to evaluate the performance of the picosatellite constellation-based network, a model that can accurately simulate the orbital physics of the constellation as well as the satellite-to-ground communication links and data traffic is necessary. The focus of this thesis was to build such a model using commercially available software and assess the effects of orbital geometries on the performance of the picosatellite constellation-based network. The research revealed that orbital planes that were inclined near the latitude of the area of interest could provide better coverage. In addition, when the satellites were spaced farther apart in the orbital plane the constellation access times were also extended. This was at a cost, however, as the link quality could be compromised. The model that was created for this research could be integrated into the Naval Postgraduate School Tactical Network Topology testbed environment to study the extension of tactical networks to orbit and allow the modelling of picosatellite architectures applied to different maritime and inland missions.

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MODELLING OF PICOSATELLITE CONSTELLATION-BASED NETWORK AND EFFECTS ON QUALITY OF SERVICE

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ABSTRACT

The military applications for miniature, low-cost satellites that could be quickly launched to provide ad-hoc tactical networks have increased in recent years. Currently, the smallest practical variant of these miniaturized satellites is known as the picosatellite. In order to evaluate the performance of the picosatellite constellation-based network, a model that can accurately simulate the orbital physics of the constellation as well as the satellite-to-ground communication links and data traffic is necessary. The focus of this thesis was to build such a model using commercially available software and assess the effects of orbital geometries on the performance of the picosatellite constellation-based network. The research revealed that orbital planes that were inclined near the latitude of the area of interest could provide better coverage. In addition, when the satellites were spaced farther apart in the orbital plane the constellation access times were also extended. This was at a cost, however, as the link quality could be compromised. The model that was created for this research could be integrated into the Naval Postgraduate School Tactical Network Topology testbed environment to study the extension of tactical networks to orbit and allow the modelling of picosatellite architectures applied to different maritime and inland missions.

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LIST OF ACRONYMS AND ABBREVIATIONS

AGI	Analytical Graphics, Inc.
AIS	Automatic Identification System
BER	bit error rate
COE	classical orbital element
GEO	geosynchronous Earth orbit
IP	Internet Protocol
LEO	low Earth orbit
MIO	maritime interception operations
NPS	Naval Postgraduate School
QoS	quality of service
STK	Systems Tool Kit
TCP	Transmission Control Protocol
TNT	tactical network topology
UDP	User Datagram Protocol

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I. INTRODUCTION

A. BACKGROUND

The development of modern space technology took off in the 1940s with the advent of rockets for military use, culminating in an intriguing arms race between the United States and the Soviet Union that became one of the highlights of the Cold War. During the decline and eventual demise of the Soviet Union, the United States became the undisputed world leader in space technology. Today, space technology has spread from the military domain to permeate all facets of modern life from enabling communications to providing entertainment. Rising costs and the stifling bureaucracy of government-led space programs have created a market gap for affordable and fast-to-deploy space-based solutions. Commercial companies have quickly filled this gap, leveraging commercial best practices to drive down the cost and development time of satellites. The introduction of cheap miniaturized satellites disrupted a field that had long been dominated by government-funded programs and commercial juggernauts. Nano and picosatellites could soon find practical applications for the military domain. The low cost to develop and launch these small satellites suggests that they could be deployed in large numbers for ad-hoc use for mission types such as maritime interception operations. It is thus necessary to be able to model networks based on small-satellite constellations to assess their performance.

B. OBJECTIVES

This study will create a simulation model component for the Naval Postgraduate School Tactical Network Topology testbed environment to study the extension of tactical networks to orbit. This study will allow the modelling of the emerging scenario of integrating cube and picosatellites in different maritime and inland missions.

C. THE RESEARCH QUESTION

This research aims to model a picosatellite constellation-based network, and investigate the effects of orbital elements such as inclination and nodal separation on

access time, link margin, and bit error rate. This thesis research aims to answer the following questions:

1. How can a picosatellite constellation-based network be modelled to study access time?
2. What is the maximum access time that the picosatellite constellation-based network can provide to a given area of interest?
3. How can a picosatellite constellation-based network be modelled to study the link margin and bit error rate?

D. SCOPE, LIMITATIONS, AND ASSUMPTIONS

There are a variety of communication architectures for constellation-based networks. For the simulation of the picosatellite constellations, the transponder architecture was assumed; each picosatellite would relay the data bit streams between the sender and the receiver as the satellite passes over the area of operation; there would be no inter-satellite link or handover mechanism; and error detection and correction would be performed at the application level. The orbits for most missions are practically circular; the altitude of the satellite remains roughly constant throughout the orbit. In an elliptical orbit, the satellite's altitude will vary between the highest point (apogee) and lowest point (perigee). At the apogee, the satellite's velocity is at the slowest providing the theoretical ability to dwell for a long duration over the area of interest. However, for most inclinations the position of the apogee will drift during the lifetime of the orbit due to perturbations [1] making the elliptical orbit impractical for picosatellites. For the simulation of the picosatellite constellations, the orbits were assumed to be circular. The research started off exploring single-plane as well as multiple-plane polar constellations; subsequently, for the inclined orbits, the study focused on single orbital plane constellations as the single-plane polar constellations had performed better.

The model that was built to simulate the picosatellite constellation-based network will only be as accurate as the parameters that were provided. All reasonable effort was expended to populate the model with realistic parameters. The mechanical characteristics of the picosatellite models were based on Bordetsky and Mantzouris' research on picosatellite constellations supporting maritime interception operations [2] so that parallels could be drawn and comparisons made with this thesis research. The parameters for the transmitter, receiver, and antenna models were based on commercially available

hardware for picosatellite application. Other models that were used included the J2 Propagator, which modelled the effects of the earth's oblate-ness on the orbital physics, the Crane 1985 rainfall model that would affect the link calculations, and so forth. Care should be taken when interpreting the results of the simulation as the constellation model was built to specific parameters. The simulation was also limited by a software integration issue preventing the data traffic from being simulated. Nevertheless, the effects of the orbital elements on access time, link margin, and bit error rate already provided a good indication of how the data traffic might perform.

E. LITERATURE REVIEW AND METHODOLOGY

Previous research had shown that a polar orbit of six satellites evenly spaced throughout the orbit could provide two to nine minutes of access time per satellite pass [2]. The inclination of such an orbit would negate the effect of nodal regression due to the earth's less-than-spherical shape [1]. This type of constellation could be used for short bursts of communication. To expand the application of ad-hoc picosatellite constellation-based networks, the orbital inclinations and spacing between the satellites could be studied to derive constellation configurations that could provide longer windows of access. Necessarily, there would be a few trade-offs in designing such constellations, and these trade-offs will be discussed.

The duration of satellite access will naturally limit the data link between the satellite and the ground node. Simply put, if the ground nodes cannot establish line of sight with the satellites, there will almost certainly be no communication. Line of sight (or access) is not sufficient to guarantee the link; the link margin and bit error rate must be sufficient for a link to be maintained. The link margin and bit error rate are directly affected by the free space loss between the satellite and the ground node. It will be shown later in the report that there is a trade-off between access duration and the guarantee of the link.

According to Comer, the packet loss, delay, and throughput are measures of the effectiveness of the network [3] and determine the quality of service. The numbers of packets received (and conversely, the numbers of packets dropped) by the destination node is directly related to the bit error rate. The vast distance between the satellite and

ground node will result in significant propagation delay. The network will never be able to send data at the maximum throughput due to the overheads that are necessary to ensure reliable transmission. Some network protocols are more efficient than others, but could be more prone to error.

The model of the picosatellite constellation-based network was built using Systems Tool Kit, a powerful software package that can accurately model space, air, and ground vehicles, sensors, and communication systems, as well as the effects of orbital mechanics and the atmosphere. The model was used to assess the effects of orbital inclinations and satellite spacing on access times, link margins, and bit error rates. QualNet, a communications analysis tool, was used to simulate the data traffic supporting a constant bit-rate application sending data from the satellite to the ground node. The two models were integrated by feeding the link calculations from Systems Tool Kit into QualNet to improve the accuracy of the data traffic simulation.

F. DEFINITIONS

This section provides the definitions of the following terms as used in the context of modelling the picosatellite constellation-based network for this thesis research. It is assumed that the reader has a basic understanding of orbital mechanics and communications networking.

1. *Access time* is the duration in which the satellite has line of sight with the ground node. One constraint that could be placed on the access time is the minimum elevation angle. Line of sight (and access) is considered to be established when the satellite is at a position higher than the minimum elevation angle.
2. *Bit error rate* is the probability that a single bit will be received incorrectly [4].
3. *Eb/N0* is the bit energy to noise density ratio [4].
4. In a *full-constellation access*, the area of interest is covered by all the satellites in the constellation consecutively such that during the pass of the constellation no gap in coverage exists.
5. *Inclination* is the angle between the plane of the orbit and the equatorial plane [1].
6. *Link margin* is the difference between the required and calculated bit energy to noise density ratio including any expected implementation loss [4]. Link margin is usually denoted in decibels (dB).
7. *Nodal separation* is the angular difference between two satellites in the same orbital plane, or how far apart they are in terms of angle.

8. *Plane separation* is the angular difference between the right ascension of the ascending nodes of two orbital planes having the same inclination. In other words, it is a measure of how far apart two orbital planes are from one another.
9. *Propagation delay* is the time required for a signal to travel across a transmission medium, such as space [3].
10. *Throughput* is the maximum rate at which data can be sent through the network [3].

G. ORGANIZATION OF STUDY

This report starts off with the examination of studies that have been conducted by other researchers pertaining to picosatellite constellation-based networks, specifically in access times and packet loss. Relevant concepts such as quality of service and different types of orbital planes will also be introduced. There will be a review of how space technology rose into prominence, the increasing popularity of miniaturized satellites, and their possible applications in the military context. Next the report will describe how the picosatellite constellation models and data traffic models were built. Some key parameters and assumptions will be provided. The results from the simulation, comprising the access time, link margin, and bit error rate, will be analyzed and presented. Finally, the report will conclude with some observations from the simulation, a discussion of the trade-offs, and recommendations for future research.

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II. LITERATURE REVIEW AND THEORETICAL FRAMEWORK

Bordetsky and Mantzouris [2], in their study on a picosatellite constellation-based private tactical network that could support reach-back communication for the boarding team in maritime interception operations (MIOs), proposed that a constellation of six picosatellites in evenly spaced polar orbits could provide up to four hours of communication coverage per day. This performance would provide sufficient time for reach-back communication in operational use. However, the four-hour coverage is non-continuous; each individual window comprises one satellite pass with a duration of two to nine minutes followed by a gap of one to two hours. While non-continuous communication coverage may be sufficient for current MIO reach-back applications, it may curtail the potential for the picosatellite constellation-based network to be used for other applications in MIO or beyond. There is reasonable scope for the further investigation of how the classical orbital elements (COEs) could influence the coverage duration, with the aim of achieving the longest possible continuous coverage per pass of the constellation. The measures of performances would include access time (in terms of constellation instead of satellite), bit error rate, and link margin. For this thesis research, transponder architecture would be assumed; each picosatellite would relay the data bit streams between the sender and the receiver using real-time links as the picosatellite passes over the area of operation; there would be no inter-satellite link or handover mechanism; and error detection and correction would be performed at the application level.

Bordetsky and Mantzouris [2] assumed a polar orbit (one in which the inclination is 90°) in their study. In a polar orbit, the picosatellites pass over every surface on earth as the earth rotates beneath the orbit. Moreover, the earth is not perfectly spherical; it bulges slightly at the equator. As a result, the orbital plane regresses westward for inclinations less than 90° and eastward for inclinations more than 90°. As shown in Figure 1, the nodal regression rate is zero when the inclination is 90°. Also, the effect is greater for picosatellites that orbit at low altitudes of around 100km.

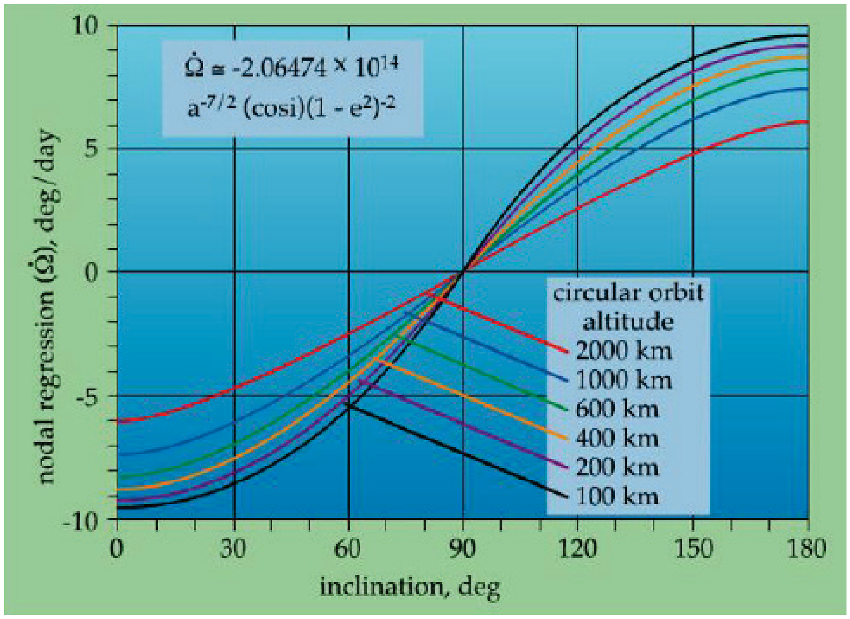

Figure 1. Nodal regression rate, from [1].

A polar orbit will be able to cover the entire surface of the earth in 12 hours, making it suitable for some applications. The ExactEarth Satellite Automatic Identification System (AIS) uses a constellation of five satellites in a polar orbit to detect commercial ships around the world and complement traditional shore-based AISs [5].

The picosatellite constellation-based network's performance could be quantitatively measured in terms of quality of service (QoS). In a packet-switched network, QoS also refers to the provisioning of specific levels of services and the mechanisms that can be used to implement these service guarantees [3]. The effectiveness of the network may be measured in terms of parameters such as *packet loss*, *delay*, and *throughput*.

Houyou et al [6]. simulated a Transmission Control Protocol and Internet Protocol (TCP/IP)–based picosatellite constellation network to investigate the effects of orbital geometry and transport protocols on packet loss. The orbital elements investigated were *alpha angle* (the distance between adjacent satellites in the same orbital plane) and *elevation angle* (the minimum angle from the ground station at which it has line-of-sight with the satellite. The study found that alpha angle of 25° was optimal in terms of packet loss; larger alpha angles led to gaps in coverage while smaller alpha angles meant that the

ground stations had less contact time with the satellites. The elevation angle affects how much of the orbit would be visible from the ground station, and hence the length of the transmission window. When comparing transport protocols, Houyou et al [6]. suggested that User Datagram Protocol (UDP) would be more efficient at utilizing the transmission windows as the protocol does not need to establish a connection nor wait for acknowledgments. TCP, on the other hand, would experience less packet loss when the bit error rate is increased due to channel degradation.

Delay, or latency, is the time the data takes to move across the network. There are a few types of delay. *Propagation delay* is the time required for a signal to travel across a transmission medium, such as space. *Access delay* is the time needed to obtain access to the transmission medium. *Switching delay* is the time taken to forward a data packet. The waiting time that a packet spends in a switch or router is the *queuing delay*. The time taken for a server to respond to a request is the *server delay* [3]. In satellite communications, propagation delay is usually the most significant due to the large distances between the satellites, as well as the distances between the satellites and ground stations. Implementing time-sensitive applications, such as voice telephony and real-time video conference, is a big challenge for most satellite communication systems because they operate from geostationary orbits.

Throughput is the rate at which data can be sent through the network. It is usually specified in bits per second (bps). The maximum throughput that a network can sustain is the capacity. Depending on the network and application protocols used, the application may not be able to transfer data at the capacity of the network. Some of the capacity is used in handshaking, sending packet headers, error correction, address resolution, retransmitting lost packets, and so forth. The effective rate at which the application can transfer data is called the *goodput* [3].

A software model that could model a picosatellite constellation-based network would be beneficial to the study of the effects of orbital elements on QoS. Propagation delay is the function of the distance between the satellite and the ground station. At the same time, packet loss is related to bit error rate, which is an indication of the quality of the link.

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III. BACKGROUND

The concept of using space as the strategic high ground materialized with the advent of the German V-2 rocket in World War II. Following the defeat of the Nazis, the United States and the Soviet Union, the two remaining super powers, essentially engaged in an arms race to build intercontinental ballistic missiles. It soon became apparent that dominance of space would become the holy grail of strategic advantage. Domestic agendas drove both countries to aggressively pursue space programs in what eventually became known as "space nationalism," a term introduced by James Clay Moltz in his book *The Politics of Space Security* [7]. The successful launch of *Sputnik*, the first man-made satellite, by the Soviet Union in 1957 was momentous in mankind's history. Fortunately the development of space programs gradually shifted toward global institutionalism as we know today. International norms were established among space-faring nations. Countries came together to develop space technologies and conduct exploratory missions. The worsening relationship between the United States and Russia due to recent events hardly affected the cooperation between the two countries on the International Space Station program; such was the importance of space as a common global interest. Decades of space experiments had taught mankind that the weaponization and dominance of space by any one nation would yield no benefit [7]. On the other hand, space held seemingly unlimited potential in terms of resources, advancement of science and technology, and making the world a more connected place.

Satellites had long become essential to the modern lifestyle, from telecommunications to television broadcast. However, access to space had been limited to government-backed programs and large corporations that could afford the high cost of developing and launching spacecraft. The CubeSat program changed that in 1999 by providing opportunities for universities to launch small satellites [8]. Private firms, governments, and even militaries soon recognized the practicality and cost-effectiveness of small satellites.

The picosatellite is essentially the basic unit of a CubeSat, defined as a 10-cm by 10-cm by 10-cm cube (or "1 U") and weighing about 1 kg. Picosatellites are launched

into space as secondary payloads riding on rockets serving other primary missions. They are usually deployed in low-earth orbit (LEO) where their lack of attitude control mechanism and propulsion capabilities (owing to size and weight constraints) means that they will be deorbited by atmospheric drag within a few months.

In the military context, the small size of the picosatellite gives it some advantage. In a highly contested space environment, a swarm of picosatellites would be harder to target and destroy completely by kinetic-kill anti-satellite (ASAT) weapons, as compared with larger satellites orbiting in LEO or geostationary orbit (GEO). Picosatellites could be produced quickly in large numbers and potentially be launched from almost anywhere in the world, even from a submarine [9]. Another possible approach could be to launch picosatellites from an aircraft such as a modified F-15E Strike Eagle [10]. Picosatellites could also be deployed to provide initial or temporary communications in hostile environments, or support short-duration missions such as MIOs.

This thesis research will create a simulation model component for the Naval Postgraduate School tactical network topology testbed environment to study the extension of tactical networks to orbit. This study will allow the modelling of the emerging cube and picosatellite architectures as applied to different maritime and inland missions.

IV. METHODOLOGY

The model of a constellation of six picosatellites as well as the satellite-to-ground node downlinks were built using Systems Tool Kit (STK). Developed by Analytical Graphics, Inc. (AGI), STK is a free-to-download physics-based 2D and 3D modeling environment to model systems such as satellites, aircraft, and sensors. The software is designed to help engineers, mission analysts, operators, and decision-makers to evaluate the performance of their systems in simulated time. The STK simulations in this thesis were performed using the license granted to the NPS for unfunded educational research. While STK simulated the physics of the constellations' orbit and the wireless satellite-to-ground node downlinks, the data traffic and routing simulation were provided by QualNet. Scalable Network Technologies, Inc. provided the single-seat one-year license for QualNet under their Educational Program for this research. The physics-based motions of the satellites and atmospheric effects models from STK were integrated with QualNet's network model using the STK-QualNet Interface module.

The analysis period for the scenario simulation was chosen as a two-day period from 6 June 2011 to 7 June 2011. This period was chosen to coincide with Bordetsky and Mantzouris' analysis [2] so that comparisons could be made. Other parameters such as the altitude of the orbit, and mass and drag profiles of the satellite were also purposefully chosen to be consistent with this study. The Crane 1985 rain model and Simple Satcom atmospheric absorption model were used to simulate elements of environmental effects in the link analysis. The J2 Propagator was defined so that the model would take into account the oblate-ness or "bulge" of the earth when evaluating orbital geometries. The Gulf of Aden was arbitrarily chosen as the area of interest because multi-national maritime interception operations take place in the Gulf, which could be an application for the picosatellite constellation-based network.

In the study conducted by Houyou et al., the researchers investigated the effects of the earth station antenna's elevation angle on packet loss. Between elevation angles of 5°, 9°, and 20°, the lowest elevation angle was associated with the least packet loss because the transmission window was the longest [6]. The UDP protocol was used for

this particular study as TCP would unduly penalize short transmission windows. However, the slant range between the satellite and the earth station will increase as the elevation angle decreases. The free space loss of the link will increase proportionately with the square of the slant range [11]. Hence, the link margin for a lower elevation angle will be worse compared with a higher elevation angle. For this thesis research, the minimum elevation angle was chosen to be 5° for practical reasons and consistency with other academic research [10, 12]. Table 1 shows the parameters that were used to model the scenario and picosatellites.

The transponder footprint was defined by the field-of-regard of the picosatellite with the assumption that omni-directional antennae were used to provide sufficient link budget in any direction, to compensate for the lack of attitude and orbital control [9].

Table 1. Scenario and picosatellite parameters.

	Parameter	Value
Scenario	Analysis Period	Start 6 Jun 2011 00:00 UTCG Stop 7 Jun 2011 23:59 UTCG
	Rain Model	Crane 1985
	Atmospheric Absorption	Simple Satcom
Area Target	Boundary	Gulf of Aden
	Minimum Elevation	5°
Satellite	Propagator	J2 Perturbation
	Altitude	310 km
	Eccentricity	0
	Cd	2.033
	Cr	1.33
	Drag Area	0.01365 m^2
	Area Exposed to Sun	0.01543 m^2
	Mass	1 kg
	Atmospheric Density	Jacchia 1970 model
	Solar Flux Sigma Level	0

A. MODELLING OF ORBITAL GEOMETRIES

To study the effects of orbital inclinations, plane separations, and nodal separations on access time, the following picosatellite constellations were modeled:

1. Single-plane polar orbit with picosatellites separated by 20°, 25°, 30°, and 35° degrees
2. Multiple-plane polar orbits, with plane separation of 5° and 10°
3. Single-plane orbits inclined at 7°, 12°, 17°, 20°, 40°, and 60° degrees, with picosatellites separated by 20°, 25°, 30°, and 35° degrees

The significance of the 12° inclined orbit was that it is at the same latitude as the Gulf of Aden. Any orbit with an inclination greater than 12° will pass directly over the Gulf at some point in time. Any orbit with an inclination less than 12° (in this case the 7° inclined orbit) will never pass directly over the Gulf. The 20°, 40°, and 60° inclined orbits were chosen to study the effects of higher inclinations on the accessibility of the constellation.

Table 2 shows a matrix that summarizes the picosatellite constellations that were modeled; each cell denotes one constellation. The ground tracks for a single-plane orbit and plane separation of 10° are shown in Figure 2 for comparison. The satellites in both constellations are phased 30° apart. The ground tracks for nodal separations of 20° and 30° are shown in Figure 3. Evidently the satellites with nodal separation of 20° are spaced closer together, compared with the satellites with nodal separation of 30°. Both constellations are inclined at 90° (polar). Figure 4 shows what the ground tracks will look like for an orbit inclined at 7° compared with an orbit inclined at 60°.

Table 2. Matrix of picosatellite constellation models.

	Nodal Separation	**20°**	**25°**	**30°**	**35°**
Orbital Planes	Polar Single Plane				
	Polar 5° Plane Separation				
	Polar 10° Plane Separation				
	Inclined 7°				
	Inclined 12°				
	Inclined 17°				
	Inclined 20°				
	Inclined 40°				
	Inclined 60°				

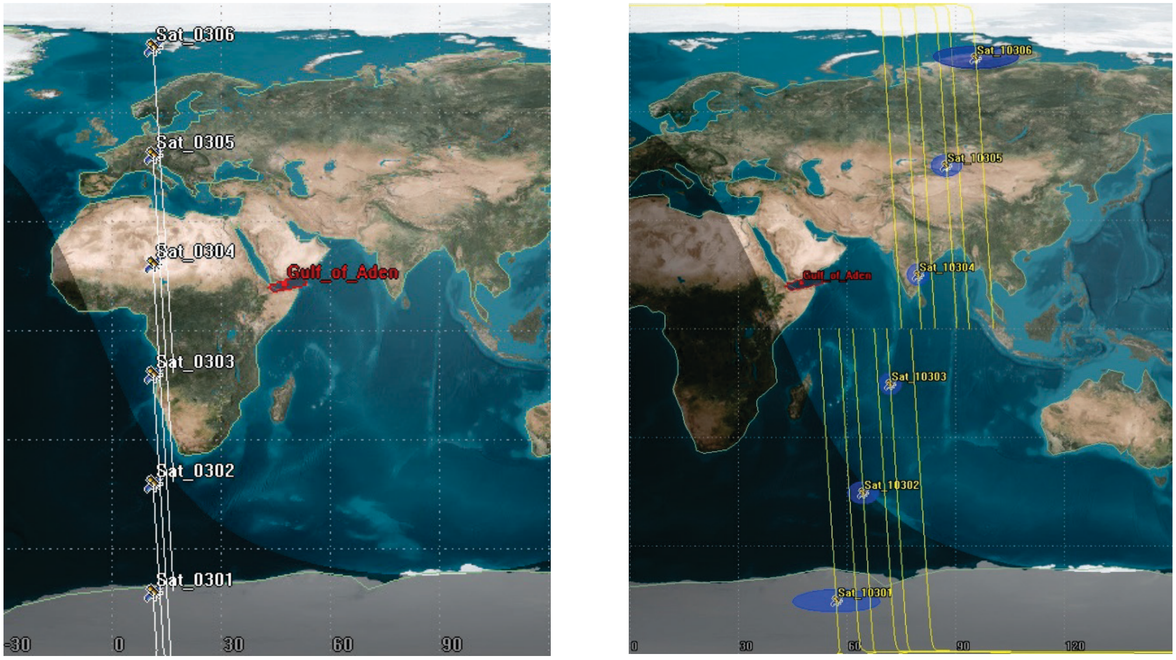


Figure 2. Comparison of ground tracks for single-plane (left) and plane-separated (right) constellations.

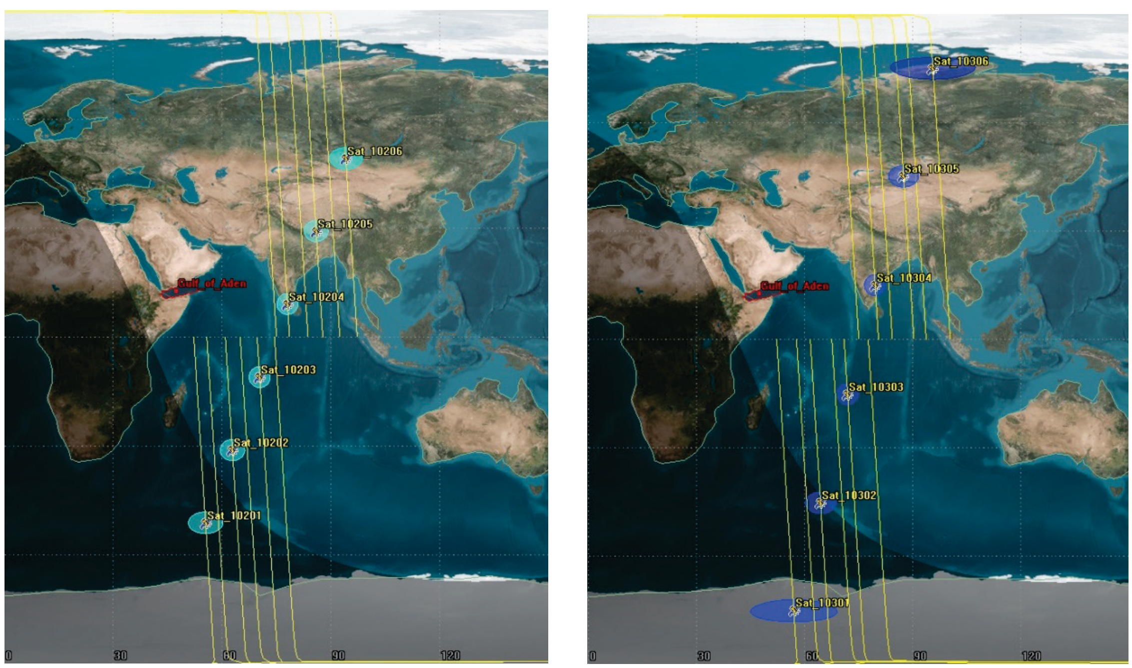
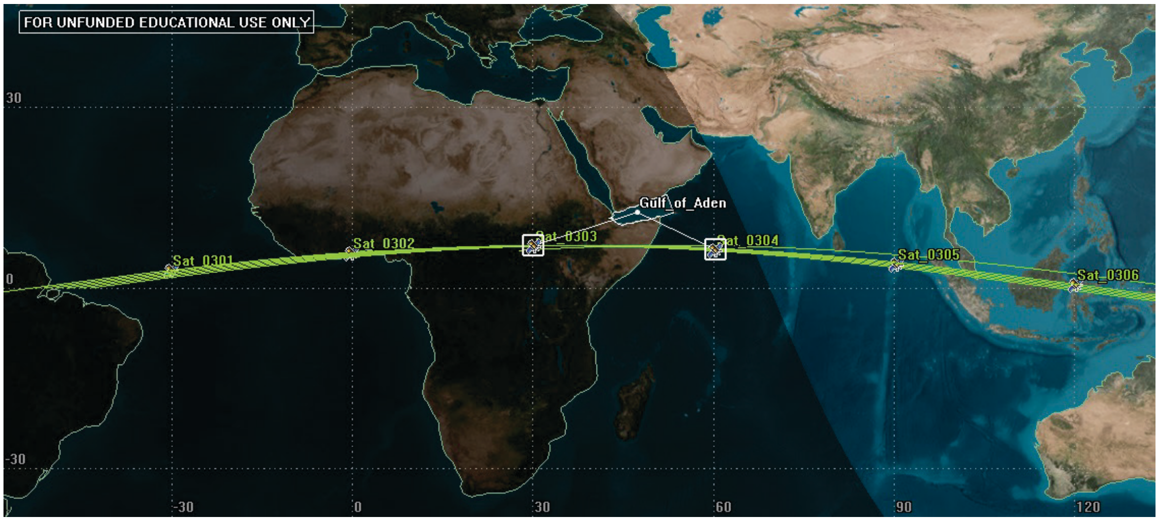


Figure 3. Comparison of ground tracks for nodal separations of 20° (left) and 30° (right).



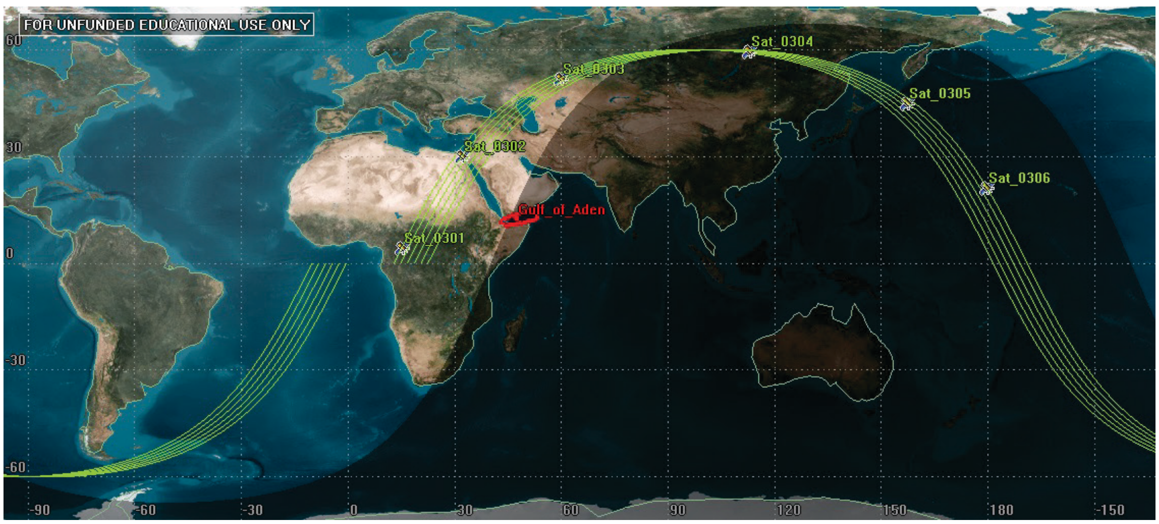


Figure 4. Comparison of ground tracks for low inclination (top) and high inclination (bottom).

B. MODELLING OF THE PICOSATELLITE COMMUNICATIONS

To study the effects of orbital inclinations, plane separations, and nodal separations on the link margin and bit error rate, each satellite was modelled with a transmitter and antenna. A receiver was also modelled to simulate a receiving node in the Gulf of Aden, as shown in Figure 5. The sensor views of the satellite and the mobile node are shown in Figure 6. The sensor views represent the fields-of-regard of the simulated Omni-directional antennas. Tables 3, 4, and 5 show the parameters that were used to model the satellite-to-ground node downlink in STK. For parameters that are not shown

in the tables, the default values were used. The parameters were based on the specifications of commercially available CubeSat-compatible hardware.

Table 3. Characteristics of satellite transmitter.

	Parameter	Value	Remarks
Model Specifications	Type	Complex Transmitter	
	Frequency	2.43 GHz	Based on amateur radio band of 2.4 – 2.45 GHz.
	Power	27 dBm	The operating power is usually set at a certain back-off from the maximum output power. In this case, the transmitter output power is adjustable in 3 dB steps, to a maximum of 30 dBm.
	Date Rate	1 Mbps	The maximum data rate of this transmitter is 2 Mbps. It can be configured to operate at full, 1/2, 1/4, or 1/8 of the full data rate.
Antenna	Type	Linked	For this simulation, the antenna was defined separately (see Table 4) so that it can be kept pointed at the area of interest for the purpose of link analysis.
Modulator	Modulation	QPSK	The transmitter implements QPSK and OQPSK modulation schemes.

Table 4. Characteristics of satellite antenna.

	Parameter	Value	Remarks
Sensor	Type	Simple Conic	A sensor element was added to the model to enable the antenna to be targeted at the area of interest.
	Cone Half Angle	60°	The patch antenna gain drops off to -3 dB at 60° beam width.
	Pointing	Targeted	Targeted at Gulf of Aden.
Antenna	Type	Parabolic	Patch antennae are commonly used for picosatellites. The antenna was modelled as an equivalent parabolic antenna with 8 dB main-lobe gain.
	Frequency	2.43 GHz	The amateur band falls between 2.4 GHz and 2.45 GHz.
	Main-Lobe Gain	8 dB	
	Efficiency	80%	Patch antennae can practically achieve 80% efficiency [12].

Table 5. Characteristics of ground receiver.

	Parameter	Value	Remarks
Model Specifications	Type	Complex Receiver	
	Frequency	Auto Track	Allows the receiver to track and lock onto the transmitter’s carrier frequency to which it is currently linking via an access, including Doppler shift
Antenna	Type	Parabolic	A parabolic ground-receiving dish was assumed.
	Frequency	2.43 GHz	
	Diameter	3 m	
	Efficiency	55%	
Additional Gain / Loss	Antenna Pointing Loss	-0.12 dB	This is equivalent to a pointing error of 2.8°, which is typical of ground-based parabolic antennae.
Sensor	Type	Simple Conic	A sensor element was added to the model to enable the antenna to be targeted at the satellite, for link analysis purposes.
	Cone Half Angle	85°	
	Pointing	Targeted	Targeted at satellite

Figure 5. STK 2D graphic showing access between a satellite and the mobile node.

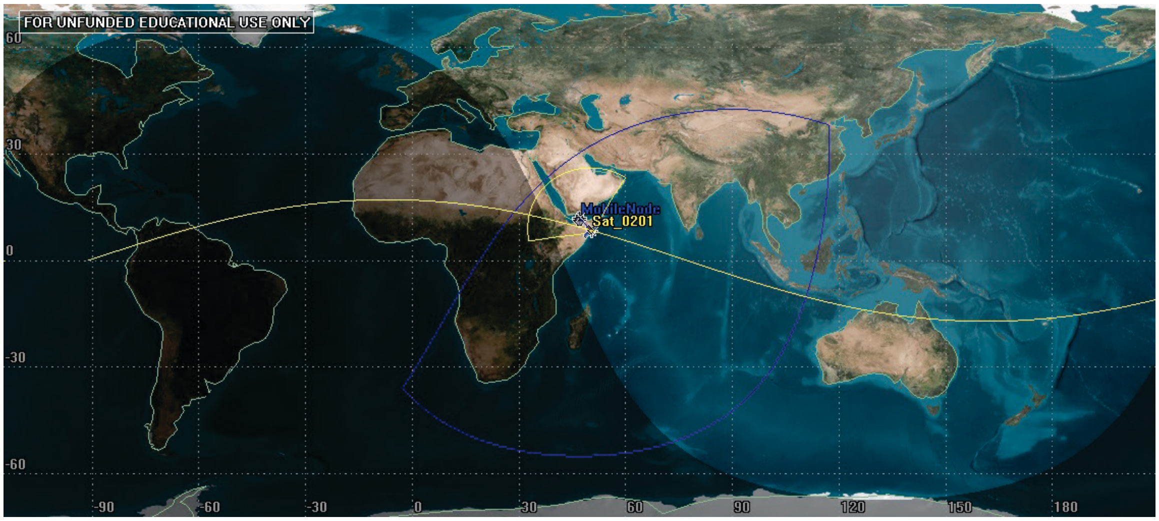


Figure 6. Sensor views of the satellite and mobile node.

The STK-QualNet interface module in STK provided a convenient way to model the data traffic of the network within the STK environment. Using the interface module, the *network interfaces*, *wireless subnet*, and *application* were defined using the parameters in Table 6. The channel frequency, data rate, frequency bandwidth, and transmission power were based on parameters used earlier for the simulation of the downlink in STK. The start and end times were an arbitrary access period in the STK simulation scenario. The rest of the parameters (such as medium access control and routing protocols) were based on the STK-QualNet interface tutorial that can be accessed from the STK help manual. Following the definition of the network, the QualNet experiment is ready to be run. The stat file viewer should show some statistics that would yield some insight on the quality of the link, for example, the number of packets received (conversely, the numbers of packets dropped), number of times the route from the source to the destination was not available, the length of packet delay, and so forth.

Unfortunately, the experiment could not be executed due to a suspected issue between the STK and QualNet interfaces even though the versions of the software used were supposed to be compatible. By the time this report was compiled, the STK technical support desk had not resolved the issue, leaving the QualNet simulation portion of this thesis for future work.

Table 6. Parameters for data traffic simulation

	Parameter	Value
Scenario Configuration	Channel Name	Downlink
	Channel Frequency	2.43 GHz
Mobile Node	Interface	Node-to-Sat
	STK Antenna Path	Defined as the mobile node's receiver antenna
Satellite Node	Interface	Sat_To_Node
	STK Antenna Path	Defined as the satellite's antenna
Wireless Subnet	Name	Downlink
	Members	Node-to-Sat Sat_To_Node
	Radio Type	Abstract
	Data Rate	1 Mbps
	Frequency Bandwidth	1 MHz
	Transmission Power	27 dBm
	MAC Protocol	Generic MAC
	No. of IP Output Queue	1
	Routing Protocol IPv4	Ad-hoc On-demand Distance Vector (AODV) [13]
Application	Source	Satellite
	Destination	Mobile Node
	Application	Constant Bit Rate (CBR)
	Items to Send	509
	Start Time	5263 sec
	End Time	5772 sec

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V. PRESENTATION OF DATA COLLECTED

The STK model was used to investigate how the number of orbital planes, plane separation, and nodal spacing influenced the coverage duration. The raw data that were generated from the simulations were the access times of the satellites on the area of interest, and the link reports for the links between the satellites and a simulated receiving node in the area of interest. A playback of the simulation scenario would quickly reveal whether there had been simultaneous accesses for two satellites in the constellation at any point in time, as shown in Figure 7. Simultaneous accesses would contribute to the full-constellation accesses that would enable the area of interest to enjoy long durations of uninterrupted coverages. For more in-depth analysis of the access times, such as the duration of the longest full-constellation access and how often they occur, Microsoft Excel was chosen for its ease of data manipulation. To do that, the access reports were exported from STK in text file format. The access reports were then opened in Microsoft Excel using a set of procedures described in the STK help manual to make them readable as Excel spreadsheets. Table 7 shows a portion of one access report after it had been imported to Excel. The data was re-arranged to show the access times in chronological order. Full-constellation accesses were identified based on the overlapping access times of six satellites consecutively, as shown in Table 9.

A similar method was used to import the link budget reports into Excel. The link budget report contained many details about the link, such as *equivalent isotropic radiated power*, *free space loss*, other losses, frequency shift due to Doppler Effect, *bit energy-to-noise density (Eb/N0)*, bit error rate (BER), and so forth. For the purpose of this analysis, the metrics of interest are the Eb/N0 and bit error rate. Therefore, the other details were hidden from view. Table 8 shows an example of the link budget report for one satellite-to-ground node downlink.

The *figure of merit (FOM)* tool in STK would have been a more efficient method of generating the constellation access times. However, during the course of the research, the use of the FOM caused the program to crash repeatedly. The advice from the STK technical support desk was that an outdated graphics card driver was probably the cause.

To avoid jeopardizing the progress of the thesis research, the graphics card driver was not upgraded.

There was no data collected from the data traffic simulation due to the technical issue between the STK and QualNet interfaces, which had not been resolved by the time this report was compiled.

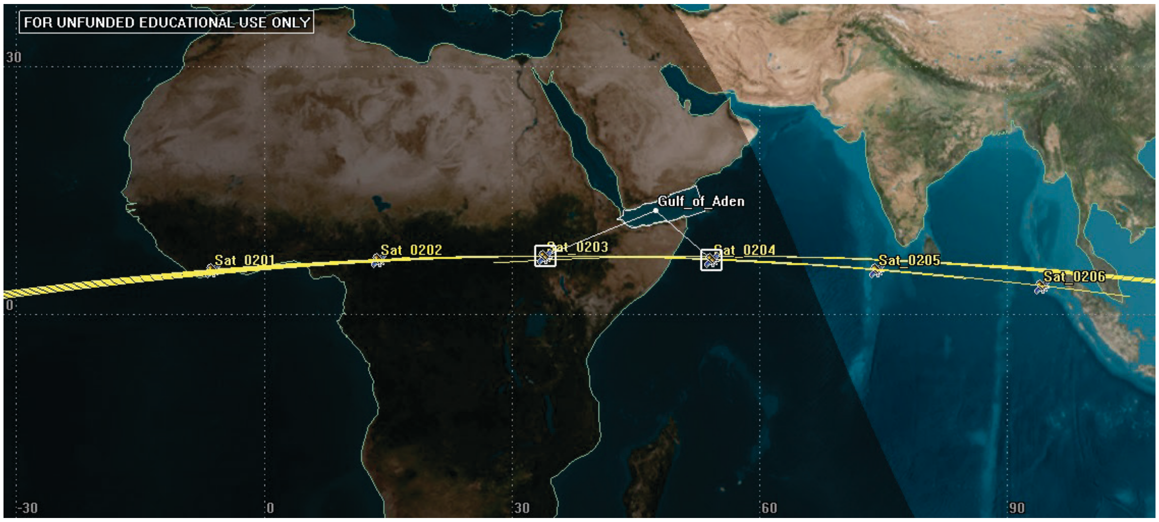

Figure 7. Ground track for inclination of 7° with simultaneous access for two satellites.

Table 7. Example of raw access report opened in Excel.

Access	Start Time (UTCG)	Stop Time (UTCG)	Duration (sec)
1	6 Jun 2011 00:00:00.000	6 Jun 2011 00:00:33.702	33.702
2	6 Jun 2011 01:27:25.434	6 Jun 2011 01:37:04.746	579.312
3	6 Jun 2011 03:03:37.916	6 Jun 2011 03:13:04.685	566.769
4	6 Jun 2011 04:40:25.714	6 Jun 2011 04:47:42.457	436.743
5	6 Jun 2011 17:35:08.922	6 Jun 2011 17:43:27.049	498.127
6	6 Jun 2011 19:10:24.276	6 Jun 2011 19:20:10.188	585.912
7	6 Jun 2011 20:46:40.910	6 Jun 2011 20:56:24.303	583.393
8	6 Jun 2011 22:23:19.350	6 Jun 2011 22:32:43.948	564.598
9	6 Jun 2011 23:59:46.345	7 Jun 2011 00:09:16.981	570.637
10	7 Jun 2011 01:35:57.192	7 Jun 2011 01:45:38.326	581.134
11	7 Jun 2011 03:12:19.716	7 Jun 2011 03:21:10.651	530.935
12	7 Jun 2011 04:49:48.768	7 Jun 2011 04:54:53.637	304.869
13	7 Jun 2011 16:08:42.133	7 Jun 2011 16:14:51.609	369.476
14	7 Jun 2011 17:43:04.952	7 Jun 2011 17:52:21.141	556.189
15	7 Jun 2011 19:18:54.396	7 Jun 2011 19:28:45.141	590.744
16	7 Jun 2011 20:55:25.522	7 Jun 2011 21:04:59.111	573.59
17	7 Jun 2011 22:32:01.838	7 Jun 2011 22:41:25.900	564.062
Access	Start Time (UTCG)	Stop Time (UTCG)	Duration (sec)
1	6 Jun 2011 01:19:24.639	6 Jun 2011 01:29:02.842	578.202
2	6 Jun 2011 02:55:36.194	6 Jun 2011 03:05:06.791	570.597
3	6 Jun 2011 04:32:18.900	6 Jun 2011 04:39:54.243	455.344
4	6 Jun 2011 17:27:16.429	6 Jun 2011 17:35:20.263	483.834
Truncated			

Table 8. Example of link budget report.

Time (UTCG)	Free Space Loss (dB)	Eb/No (dB)	BER
6 Jun 2011 01:21:56.835	166.2587	6.3662	1.62E-03
6 Jun 2011 01:22:56.000	164.3214	9.8703	5.27E-06
6 Jun 2011 01:23:56.000	161.8333	12.9086	2.04E-10
6 Jun 2011 01:24:56.000	158.5462	17.1602	1.01E-24
6 Jun 2011 01:25:56.000	154.4605	23.7294	1.00E-30
6 Jun 2011 01:26:56.000	153.392	25.8341	1.00E-30
6 Jun 2011 01:27:56.000	157.2679	19.0139	1.00E-30
6 Jun 2011 01:28:56.000	160.871	14.095	3.87E-13
6 Jun 2011 01:29:56.000	163.5841	10.7899	4.84E-07
6 Jun 2011 01:30:56.000	165.6936	7.748	2.79E-04
6 Jun 2011 01:31:14.166	166.2465	6.3785	1.60E-03
6 Jun 2011 02:58:13.725	166.2525	6.3724	1.61E-03
6 Jun 2011 02:59:13.000	164.2951	9.9023	4.89E-06
6 Jun 2011 03:00:13.000	161.7692	12.9861	1.42E-10
6 Jun 2011 03:01:13.000	158.3786	17.395	5.47E-26
6 Jun 2011 03:02:13.000	153.9564	24.6971	1.00E-30
6 Jun 2011 03:03:13.000	152.6827	27.3504	1.00E-30
6 Jun 2011 03:04:13.000	156.9812	19.4509	1.00E-30
6 Jun 2011 03:05:13.000	160.748	14.2489	1.51E-13
6 Jun 2011 03:06:13.000	163.5206	10.8654	3.89E-07
6 Jun 2011 03:07:13.000	165.6569	7.8083	2.56E-04
6 Jun 2011 03:07:31.778	166.2331	6.3918	1.58E-03
6 Jun 2011 04:34:59.974	166.2404	6.3843	1.59E-03
6 Jun 2011 04:35:59.000	164.6302	9.4562	1.33E-05
Truncated			

Table 9. Example of access report re-arranged for analysis.

Satellite	Access	Start Time (UTCG)	Stop Time (UTCG)	Duration (sec)	Gap to Next Access (h:mm:ss)	Constellation Access Duration (h:mm:ss)
1	1	6 Jun 2011 00:00:00.000	6 Jun 2011 00:00:33.702	33.702	0:46:47	0:00:34
6	1	6 Jun 2011 00:47:20.759	6 Jun 2011 00:56:53.498	572.74		0:49:44
5	1	6 Jun 2011 00:55:21.866	6 Jun 2011 01:04:56.053	574.187		
4	1	6 Jun 2011 01:03:22.872	6 Jun 2011 01:12:58.480	575.608		
3	1	6 Jun 2011 01:11:23.791	6 Jun 2011 01:21:00.746	576.955		
2	1	6 Jun 2011 01:19:24.639	6 Jun 2011 01:29:02.842	578.202		
1	2	6 Jun 2011 01:27:25.434	6 Jun 2011 01:37:04.746	579.312	0:46:26	
6	2	6 Jun 2011 02:23:31.075	6 Jun 2011 02:33:10.842	579.767		0:49:34
5	2	6 Jun 2011 02:31:32.137	6 Jun 2011 02:41:10.432	578.295		
4	2	6 Jun 2011 02:39:33.328	6 Jun 2011 02:49:09.642	576.314		
3	2	6 Jun 2011 02:47:34.673	6 Jun 2011 02:57:08.433	573.76		
2	2	6 Jun 2011 02:55:36.194	6 Jun 2011 03:05:06.791	570.597		
1	3	6 Jun 2011 03:03:37.916	6 Jun 2011 03:13:04.685	566.769	0:46:53	
6	3	6 Jun 2011 03:59:57.977	6 Jun 2011 04:08:33.211	515.234		0:32:08
5	3	6 Jun 2011 04:08:02.386	6 Jun 2011 04:16:25.463	503.078		
4	3	6 Jun 2011 04:16:07.305	6 Jun 2011 04:24:16.502	489.198		
3	3	6 Jun 2011 04:24:12.788	6 Jun 2011 04:32:06.047	473.259	0:00:13	
2	3	6 Jun 2011 04:32:18.900	6 Jun 2011 04:39:54.243	455.344	0:00:31	0:07:35
Truncated						
4	18	7 Jun 2011 23:44:16.819	7 Jun 2011 23:53:51.071	574.252		
3	18	7 Jun 2011 23:52:17.835	7 Jun 2011 23:59:59.000	461.165		
				MAX	10:51:09	0:49:55
				MIN	0:00:04	0:00:34
				AVERAGE	0:58:03	0:21:21

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VI. DATA ANALYSIS/INTERPRETATION

The STK model was used to investigate how the number of orbital planes, plane separation, and nodal spacing influenced the coverage duration. The aim is to achieve the longest possible continuous coverage per pass of the constellation, which theoretically will occur when all six satellites in the constellation pass overhead continuously without any gap in coverage. The measures of performance would include the longest access time, numbers of full-constellation accesses, BER, and link margin.

A. EFFECTS ON ACCESS

The longest access time refers to the longest period during which the area of interest was covered by the constellation, during the time period of the simulation. The access time is the window during which nodes in the area of interest will be able to communicate with the constellation. Full-constellation access refers to an access in which all six satellites of the constellation pass continuously over the area of interest without any gap in coverage. The longest access time logically must coincide with a full-constellation access.

Figure 8 shows that the longest constellation access time was achieved using a single plane inclined at 12° with the picosatellites spaced 35° from one another. In other words, such a constellation would allow nodes in the area of interest to have access to the satellites for a continuous time window of 56 minutes (from Table 10). Inclined orbits achieved longer constellation access times compared with polar orbits.

Figure 9 shows that the highest numbers of full-constellation accesses were achieved using single-plane orbits inclined at 7°, 12°, and 20°, with the picosatellites spaced 20° from one another. Such constellations would allow nodes in the area of interest to have access to all six satellites continuously in the same time window without gaps in coverage, up to 15 times (from Table 11) during the two-day mission duration. Polar orbits showed less full-constellation accesses than inclined orbits.

The results were as expected and consistent with orbital physics. Orbits inclined near the latitude of the area of interest were expected to pass more frequently over the

area. Satellites spaced too close to one another would result in overlaps in coverage. The longest constellation access times were inversely related to the numbers of full-constellation accesses. When satellites were spaced far from one another, the constellation coverage could be stretched over a longer period of time; however, such occurrences were less frequent compared with satellites spaced closer together. These results will have implications on how LEO picosatellite constellations are deployed; there will be a trade-off between the time-length of continuous coverage and how often such full-constellation coverages are desired.

Table 10. Effects of nodal spacing and plane separation on longest constellation access time (in minutes and seconds).

	Nodal Separation	**20°**	**25°**	**30°**	**35°**
Orbital Planes	Polar Single Plane	32:35	39:02	29:58	07:50
	Polar 5° Plane Separation	31:30	37:29	14:50	07:48
	Polar 10° Plane Separation	21:08	24:41	14:34	07:51
	Inclined 7°	36:08	42:49	49:31	09:22
	Inclined 12°	36:40	42:21	50:03	56:45
	Inclined 17°	36:34	43:14	49:55	56:36
	Inclined 20°	36:29	43:09	49:49	56:28
	Inclined 40°	35:45	42:17	48:47	55:18
	Inclined 60°	34:24	40:47	47:07	8:52

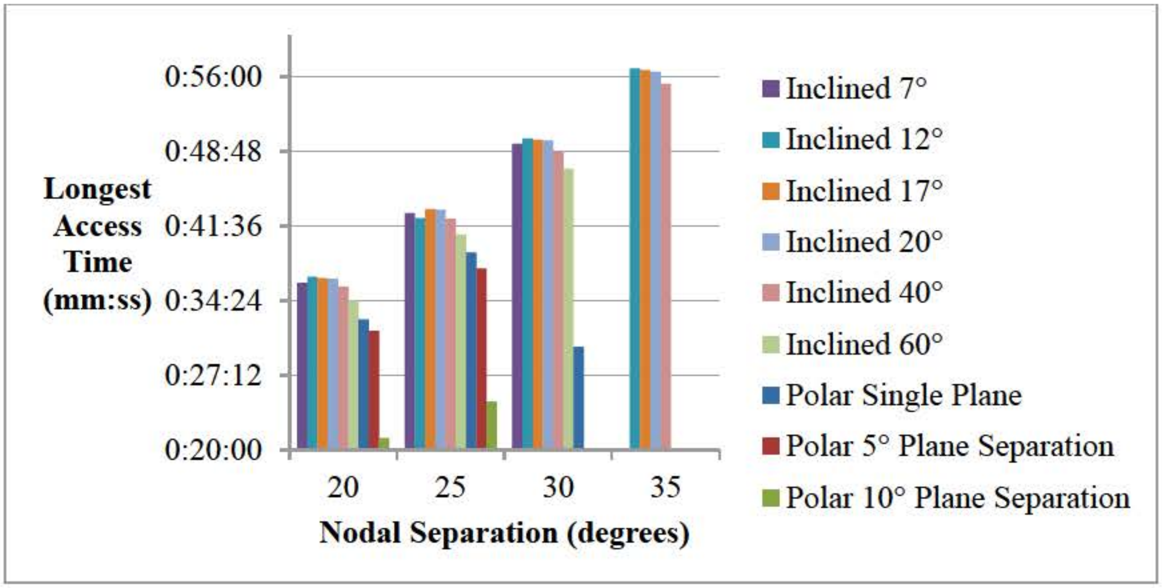

Figure 8. Graph of effects of nodal spacing and plane separation on longest constellation access time.

Table 11. Effects of nodal spacing and plane separation on numbers of full-constellation accesses.

	Nodal Separation	**20°**	**25°**	**30°**	**35°**
Orbital Planes	Polar Single Plane	4	3	0	0
	Polar 5° Plane Separation	2	1	0	0
	Polar 10° Plane Separation	0	0	0	0
	Inclined 7°	15	13	9	0
	Inclined 12°	15	14	12	8
	Inclined 17°	14	14	12	10
	Inclined 20°	15	14	13	4
	Inclined 40°	6	5	3	1
	Inclined 60°	7	5	1	0

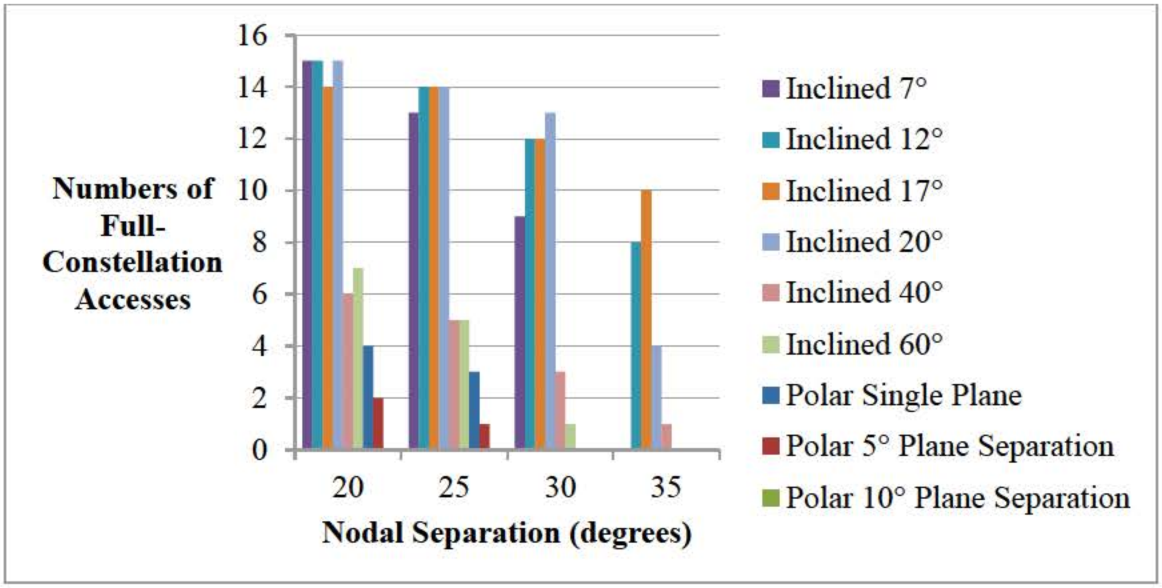

Figure 9. Effects of nodal spacing and plane separation on numbers of full-constellation accesses.

B. EFFECTS ON LINK

To demonstrate the effect of nodal separation, the satellite-to-node downlinks across the time periods of two arbitrarily chosen full-constellation accesses in the 17° inclined orbital plane were analyzed. For the constellation with 20° satellites spacing, the window that was chosen for analysis was 7 June 2011 from 18:52 to 19:28, which was the occurrence of the longest full-constellation access (36 minutes). For the constellation with 35° satellites spacing, the window that was chosen for analysis was 6 June 2011 from 19:59 to 20:56, which was also the occurrence of the longest full-constellation access (56 minutes).

Modulation is the process in which the characteristics of a carrier signal are varied by the information to be transmitted. Quadrature Phase Shift Keying (QPSK) is one modulation technique in which four carrier phases are used to represent data. These four symbols are formed using two bits. To recover the transmitted bit accurately, the bit energy Eb must be sufficiently higher than the noise density N0. For QPSK, the Eb/N0 required to achieve a BER of 10^{-5} or better is 9.6 dB. The link is usually designed with a 3dB margin above the required Eb/N0 to allow for losses [4].

When the satellites were spaced 20° apart, a receiving node in the area of interest was able to establish a downlink with sufficient link margin (of at least 3dB) with at least one satellite at any time during the full-constellation access, as shown in Figure 10. The signal from one satellite dropped below the required margin when the signal from another satellite climbed above the margin. This feature may indicate that 20° could be close to the optimal spacing. Correspondingly, the achievable BER was at least 10^{-5} throughout the access period, as shown in Figure 11.

For nodal spacing of 35° however, Figure 12 shows that the Eb/N0 will occasionally fall below the required 3dB margin as the overlap between satellite coverages were insignificant. Correspondingly the achievable BER will occasionally be worse than 10^{-5}, as shown in Figure 13.

In conclusion, when satellites are spaced farther apart (say 35°), the longest full-constellation access could be as much as 20 minutes *longer* compared with satellites spaced closer together (say 20°). However, the required link margin and BER will not be maintained throughout the entire access period causing the link to be intermittent. The data traffic simulation was not analyzed due to the technical issue between the STK and QualNet interfaces, which prevented data from being collected. The issue had not been resolved by the time this report was compiled.

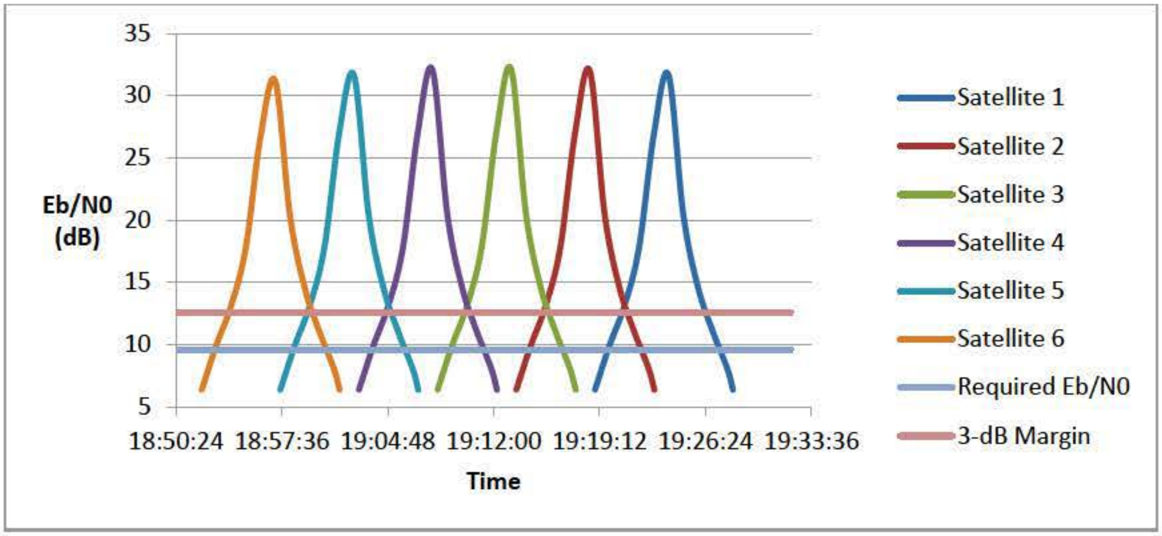

Figure 10. Graph of Eb/N0 across one full-constellation access for 20° nodal separation.

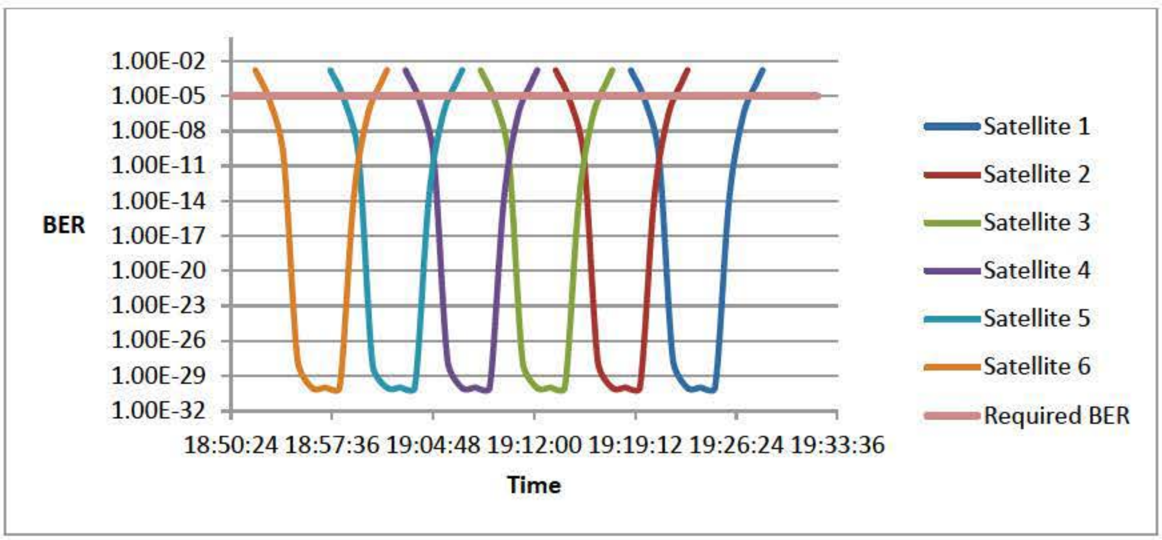

Figure 11. Graph of BER across one full-constellation access for 20° nodal separation.

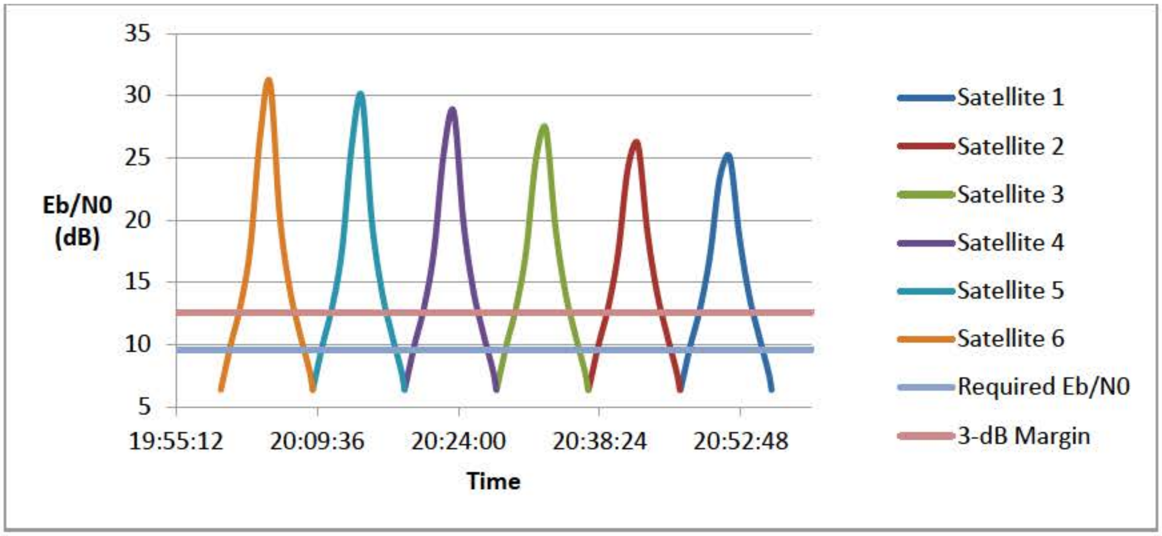

Figure 12. Graph of Eb/N0 across one full-constellation access for 35° nodal separation.

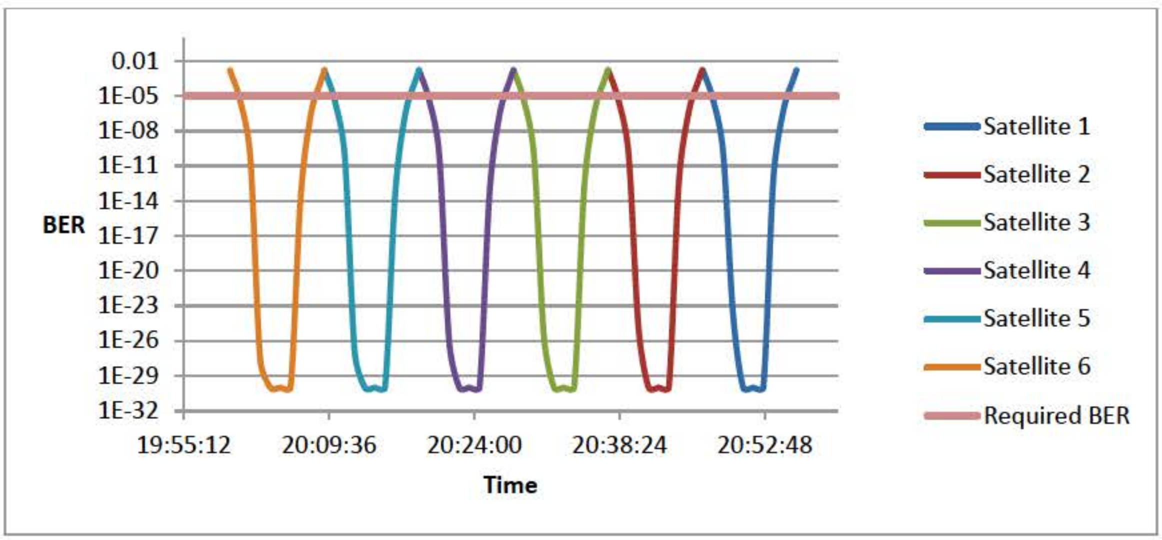

Figure 13. Graph of BER across one full-constellation access for 35° nodal separation.

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VII. CONCLUSIONS AND RECOMMENDATIONS

As miniaturized satellites gain popularity in the commercial, academic, and military domains, the demand for better performance can only increase. The accessibility of the picosatellite constellation will affect the quality of the wireless link and therefore the quality of the data traffic. Factors that will affect the accessibility of the picosatellite constellation are the inclination of the orbit, the spacing between the satellites, and the altitudes of the satellites. The orbital inclination and satellites' altitudes directly affect the amount of free space loss and contribute to the link margin and bit error rate. The inter-satellite spacing determines whether the satellite-to-ground node downlink can maintain the required link margin and bit error rate throughout the entire pass of the constellation. The trade-offs depend on which is more critical to the mission—long continuous access time or link quality. To achieve guaranteed link quality, the length of the access time could be sacrificed.

For the polar orbits, the single-plane constellation provides longer access time compared with the multiple-plane constellation. Another practical consideration for favoring the single-plane constellation, which was not apparent from the simulation, is the relative ease of launching the picosatellites into a single orbital plane compared with multiple planes. For the single-plane constellation, a single pass by the launcher could place all the picosatellites into the required orbital plane; in the multiple-plane constellation, the picosatellites may not have the propulsion capabilities to change the ascending node of their orbits.

Planes that were inclined near the latitude of the area of interest would provide more full-constellation accesses throughout the mission duration, guaranteeing long continuous coverage with each pass. The spacing between satellites would determine the lengths of the full-constellation accesses. Constellations with closely spaced satellites resulted in shorter full-constellation accesses with a guaranteed link. On the other hand, satellites that were spaced farther apart delivered longer full-constellation accesses, but the link could be intermittent. As shown in the simulation results presented in this report, the link margin and bit error rate were unsatisfactory when the satellites were spaced 35°

apart for altitudes of 310 km, even though the constellation had line of sight with the area of interest for nearly one hour. One of the recommendations for future work would be to investigate the methods of optimizing the spacing between the satellites. Figure 10 shows the Eb/N0 profile of a constellation that could be almost optimal.

In the comparison between single-plane orbits, the inclined plane achieved longer constellation access time compared with the polar plane. However, the polar constellation could be used for applications that require global coverage but not long continuous access time.

Although the simulation of the network data traffic was not completed, the investigation on orbital geometries has already revealed much about the effects of orbital elements on the quality of the link. Upon resolution of the interface issue between STK and QualNet, the data traffic could then be incorporated into the simulation of the picosatellite constellation to study how packet loss and packet delays would be affected by orbital geometries. The application of picosatellite constellation-based networks is a nascent field. There is a reasonable amount of scope for the research of picosatellite technologies (such as self-steering antennae and autonomous swarm intelligence), network resilience, network security, and constellation design. The cyber-physical integration of test bench data with STK and QualNet could help to further validate the simulation models.

The transponder footprint of the picosatellite has been limited by omni-directional antennae due to the lack of precision-steering capability within the small form factor of the satellite. However, recent developments in self-steering antenna technology may pave the way for antennae on picosatellites to achieve directionality and higher gain [14, 15]. For future research, the effects of directional antennae could be incorporated into the model, recognizing the possibility that directional antennae could be gaining popularity over omni-directional ones.

Pegher and Parish purported that the traditional constellation design methods, such as the Walker Constellation, could be improved using genetic algorithms [16]. Although Pegher and Parish's work was aimed at optimizing global coverage for satellite

constellations, the genetic algorithm method could be adapted to improve continual accessibility for ad-hoc picosatellite constellation-based networks.

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